干旱区地理
ARID LAND GEOGRAPHY

塔里木河下游生态输水条件下胡杨林生态系统恢复研究

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摘 要：基于文献阅读，对塔里木河下游生态输水条件下胡杨林生态系统的恢复响应进行了讨论分析。生态输水显著抬升了地下水位，降低了地下水矿化度与土壤干旱指数，有效改善了塔里木河下游胡杨林生态系统的生境；胡杨复壮明显，距河道50 m胡杨冠幅最大增长达511.20%，距河道500 m内胡杨枯枝比平均小于0.15。输水后，下游胡杨树干径向生长平均增加62.80%，以胡杨为建群种的下游荒漠河岸林植被面积从2000年的492 km^2增加到2020年的1423 km^2，其中，低、中、高覆盖度植被面积分别增加20.80%、448.00%和190.00%；下游生态环境与植被群落对输水响应敏感，随输水量变化响应波动；现有输水模式因缺乏面上水文过程而难以保障下游胡杨林的有效更新，胡杨种群历经输水20 a依然保持“倒金字塔”型的退化龄级结构，并出现显著的性比偏雄与性别空间分异；胡杨群落依然处于恢复演替的初级阶段且不稳定，下游生态系统退化态势尚未彻底扭转。基于研究综述，探讨了塔里木河下游生态恢复中存在的问题，提出“优化输水方案，扩大受水面积和采取更加积极的恢复措施”的建议。

关 键 词：塔里木河；生态输水；胡杨；生态恢复

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塔里木河是世界第五大内陆河，地处暖温带极端干旱区，生态系统极为脆弱[1-2]。沿塔里木河流域发育的以胡杨（*Populus euphratica* Oliv.）为优势建群种的荒漠河岸林是中亚重要的荒漠森林生态系统，为区域提供着包括资源供给、气候调节、风沙防护、水土保持和生物多样性保护等多重生态服务功能[3-5]，同时，也是重要的胡杨基因库[6-7]。然而，由于塔里木河流域各主要源流区大规模水土资源开发，导致水资源在流域上下游空间分布的逐渐失衡，下游来水逐年减少。自20世纪70年代起，塔里木河下游近400 km河道长期断流，尾闾湖泊台特玛湖干涸，塔里木河下游胡杨林生态系统严重退化衰败，荒漠化加剧，生物多样性显著降低，“绿色走廊”濒临消失，生态环境日趋恶化，成为20世纪末中国西北干旱区生态问题最为突出的典型区之一[1,8]。国家从2000年开始向塔里木河下游实施生态输水，以挽救垂死的胡杨林。本文通过梳理塔里木河下游实施生态输水以来胡杨林生态系统恢复的相关研究，归纳了生态输水条件下胡杨林生态系统的恢复状况，探讨了生态输水中存在的问题，并提出对策建议，旨在为塔里木河流域的二期治理与塔里木河下游胡杨林生态系统保育恢复提供参考与支撑。

1 生态输水对塔里木河下游胡杨林生态系统生境的改善

1.1 地下水位有效抬升，随生态输水量变化波动

地下水是干旱区自然植被赖以生长与生存的重要水源，是控制塔里木河流域胡杨林植被群落分布、演替和生长的关键生境因子[9-10]。胡杨凭借其地下水湿生特性，得以在极端干旱的塔里木盆地生存、繁衍，并成为该区域具有重要生态服务价值的

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荒漠河岸林生态系统的优势建群种[5]。塔里木河下游长时间断流导致地下水位持续下降，生态输水前下游沿河地下水埋深普遍已经增大至8~12 m，这是造成沿河胡杨林显著衰败及群落物种多样性受损的重要原因[11]。生态输水下，塔里木河下游的地下水位显著抬升[12-13]，下游距河道500 m范围内地下水埋深由生态输水前2000年的平均8.57 m恢复到2020年的平均4.40 m。这是持续生态输水对沿河浅层地下水有效补给的结果。结合输水中各断面水量监测，利用水平衡方法测算，大西海子水库下泄水量中补给沿岸土壤包气带、地下水和沿途河面蒸发耗散及进入台特玛湖的水量分别占44.50%、43.70%、3.10%和8.70%，有88.20%的水量补给了塔里木河下游沿岸包气带与地下水，有效改善了胡杨林生境[14]。但同时，基于多年的地下水位监测，我们也不难发现，塔里木河下游的地下水位随不定期的生态输水水量变化波动明显。在输水早期（2000—2003年），经5次大水量生态输水后，地下水响应明显，并在2003年地下水位恢复至一个阶段峰值，其中下游英苏村以上的区段地下水位抬升幅度超过80.00%，横向影响范围超过1000 m[14-15]。2004—2009年伴随输水量的下降，特别是2007—2009年，上游来水锐减，大西海子连续3 a下泄水量不足0.25×10^8 m^3，塔里木河下游各区段地下水位显著下降；2010年后，随塔里木河向下游输送水量加大，下游两岸地下水位再次抬升，但单一年份的输水量下降同样会导致沿岸地下水位大幅波动与显著下降，比如2014年[14]，保障塔里木河下游相对稳定的河道内生态流量与下泄水量是维持两岸地下水位稳定的关键。

1.2 地下水矿化度显著降低，两岸淡化带范围扩大

塔里木河下游第四纪沉积层厚度超过200 m，含水层为颗粒细小的细沙和粉细沙层为主，并夹杂多个黏土层，透水性和导水能力不佳[12]。区内可被生态系统利用的地下水主要是具有自由表面的潜水，多为塔里木河渗漏形成，水质不好，矿化度3~10 $g\cdot L^{-1}$，局部与河道或古河道距离较近区段潜水矿化度1~3 $g\cdot L^{-1}$或<1 $g\cdot L^{-1}$，属于河水冲淡型透镜体，厚度一般30 m左右。多年河道断流使得塔里木河下游可被植被利用的浅层地下水失去补给，随同地下水位下降，地下水矿化度也显著升高，输水前塔里木河下游两岸的地下水矿化度已经普遍在3 $g\cdot L^{-1}$以上，甚至为大于10 $g\cdot L^{-1}$的盐卤水，这进一步加剧了下游胡杨的渗透胁迫与整体退化[16]。经过生态输水，塔里木河下游两岸的地下水矿化度显著下降，沿河两岸横向1 km范围内平均由输水前的4~11 $g\cdot L^{-1}$左右降至1~5 $g\cdot L^{-1}$[17]。其中下游上、中段的地下水矿化度由输水前的4~5 $g\cdot L^{-1}$下降到1~3 $g\cdot L^{-1}$，两岸淡化带影响范围最远延伸至距河道1 km左右[14]。地下水矿化度与生态输水量显著相关，2005—2008年，随输水量减少，地下水矿化度表现出明显的上升波动[14]。

1.3 生态输水缓解了全球升温可能对下游胡杨林生态系统的负面影响

气候变化被认为是影响全球生物多样性的一个重要威胁[18]，全球快速升温将对各类生态系统产生显著影响，一些研究已经揭示了气候变化对植物生长与发展的负面作用[19-20]。中国西北干旱区对全球气候变化响应尤为敏感，升温更快。过去几十年，这里的气温以0.33~0.39 ℃·$(10a)^{-1}$增幅上升[21-22]。尽管分析显示，中国西北干旱区的降水也在增加，但升温导致的水循环加剧和干旱区蒸散发改变更趋明显，并抵消了降水增加的效应[23-24]。研究分析显示，塔里木河下游过去60 a标准化降水蒸散指数（SPEI）指示的气象干旱呈显著增强趋势，但输水后沿河胡杨林立地的土壤水分随输水对包气带和地下水的补给作用而有效改善，胡杨林生境土壤干旱指数整体呈下降趋势，生态输水在一定程度上抵消并阻断了全球升温引发的气象干旱对塔里木河下游胡杨林可能带来的负面效应[14]。基于胡杨树木年轮的分析也发现，受生态输水影响，当塔里木河下游沿岸地下水埋深小于6 m的情况下，升温对胡杨的生长具有促进作用[9]。

2 胡杨生长与生理生态过程对生态输水的响应

2.1 塔里木河下游胡杨显著复壮

历经几十年的断流与生态退化，目前塔里木河下游的荒漠河岸林植被带主要分布在河道两侧1 km左右的范围内[25]。胡杨的生物量主要分布在距离河道700 m范围内，占到了塔里木河下游胡杨总生物量的91.37%，且胡杨生物量整体在横向上随着距河道渐远而减少[26]。生态输水对河岸两侧生境的

主要影响范围与胡杨林的分布区域基本重合，输水显著改善了胡杨个体的长势，特别是近河道500 m范围内的胡杨[12,27]。输水后沿河胡杨的当年生小枝长度及枝条上叶片数与叶长、叶宽、叶重均明显增加[28]；相比输水前，在距离河道50 m处，胡杨冠幅最大增加了511.20%；距离河道500 m范围内胡杨成株的枯枝比显著下降，平均小于0.15，但距离河道1000 m和1500 m处胡杨枯枝比仍高达0.42和0.74[29-30]；胡杨树干的径向生长也在输水后平均增长62.80%，且胡杨枝下高呈下降趋势[15,30]。输水后胡杨的新增生物量显著增加了154.40%[31]，胡杨林郁闭度在离河道50 m处比输水前增加了380.80%[14]。这些都显示，生态输水有效遏制了塔里木河下游胡杨林的衰败，胡杨个体长势出现明显复壮。

2.2 胡杨生理生态活性显著提升

塔里木河下游胡杨可利用的水分主要来源于地下水与深层土壤水[32]。生态输水前受地下水位持续下降与土壤水分降低、地下水矿化度升高与土壤盐分增加等生境恶化影响，下游胡杨处在不同程度的干旱胁迫与渗透胁迫中。研究已经揭示，干旱与盐胁迫会从器官形态结构[33]、植株个体生长与生物量分配[34]、光合作用[35]、水力传导与渗透调节[16,36]、内源激素调控[37]等多个方面影响植物生理生态过程。输水通过抬升地下水位、改善水质和土壤水分条件，促进沿河胡杨的光合速率与光合活性[35,38]；使得胡杨叶片正午保持更高水势与更好的水分条件[16,38]；改善并恢复胡杨木质部的水力传导与干旱胁迫下栓塞的木质部导管[39-40]，使胡杨木质部中径流显著提升[41]，为胡杨生长提供更好的水分保障，并进一步改善胡杨的光合同化作用与整体生长。对比其他几个河岸林杨树种，胡杨干旱胁迫下的脆弱性相对更大，对干旱响应更为敏感，干旱条件下胡杨木质部栓塞程度更高、水力导度损失更大[36]。在野外常常表现出因水力传导失败造成的死梢与枯枝，这是干旱胁迫的结果，也是胡杨将更多生物量分配至吸水根系的一种适应与应对干旱的策略。水分条件一旦改善，胡杨能够在复水后逐步恢复包括光合、气孔导度、水力传导和生长调节等功能[36]，这是胡杨在输水后明显复壮的生理生态基础。陈亚宁等多位学者基于输水前后胡杨林群落内植被生理生态指标对地下水位的响应，确定并提出了塔里木河下游胡杨林生态系统恢复的适宜生态水位在2~4 m左右，胁迫地下水位6 m，临界地下水位9~10 m左右的结论[11,42-43]，为塔里木河下游胡杨林生态系统的恢复提供了重要的支撑。

3 生态输水对胡杨种群发展与群落格局的影响

3.1 输水遏制了胡杨的衰败，但未扭转种群结构老化、更新乏力和退化的态势

基于塔里木河下游生态监测断面多年的野外调查监测和区域尺度上的遥感监测分析可知，生态输水基本遏制了塔里木河下游胡杨的衰败，两岸胡杨植株个体得以不同程度复壮，植株冠幅、郁闭度及生物量均增加、个体径向生长与生理指标明显改善[8,14]。输水前下游胡杨普遍死梢、衰败凋亡的颓势得到遏制[31]。调查发现，胡杨的种群更新在输水后仅出现在近河道300 m范围内，相对较高比例的幼株也只是出现在近河道处[6,30]，并且更新的幼株多为无性繁殖产生。生态输水抬升了地下水位，改善了胡杨生存的生境，这对塔里木河下游衰败的胡杨是一个拯救的过程，但是却难以实现胡杨的落种更新[29]。这是因为，胡杨实生苗只有在洪水作用下的洪泛环境与土壤湿润处方能落种定植[5]。由于具R策略属性的有性繁殖受抑，胡杨种群更新乏力，种群及植株个体适合度均不同程度下降。历经生态输水20 a，塔里木河下游胡杨种群的龄级结构依然呈“倒金字塔”型，种群发展动态指数与种群密度统计结果均指示区内胡杨种群衰退的趋势尚未彻底扭转[44]。近河道处胡杨克隆幼株比例随地下水抬升增大是生态输水对胡杨种群结构重要改善与促进，并且，克隆繁殖可以在地下水位浅但是由于上层土壤盐分较高、阻止落种更新的区段实现种群更新[5,45]。试验分析也显示，在相似地下水位与生境条件下，由于胡杨成株对其克隆幼株的水分生理整合，使其克隆繁殖具有K策略的属性，进而克隆幼株能够在极端干旱生境下较实生幼株具有相对更好的水分获取能力与生存优势[46]。但在现实中，胡杨根蘖繁殖的速率和有效性难以满足塔里木河下游胡杨种群的更新需求，且过渡依赖无性繁殖对胡杨种群的基因多样性可能产生的影响尚不确定。调查发现，塔里木河下游胡杨种群性比显著偏雄，且性别空间分异明显，这种趋势在下游胡杨无性繁殖

下可能进一步恶化,并加剧种群的退化[44]。

3.2 胡杨林群落植被长势好转,但群落物种多样性变化不显著,稳定性不足

塔里木河下游的生态输水工程有效改善了胡杨林群落的生境,尤其是水分条件的改善对下游胡杨林群落内植被长势有明显促进作用[29,47-49]。下游胡杨林生态系统自然归一化植被指数(NDVI)随生态输水整体呈增加趋势,NDVI由输水前的平均0.14提升至目前的0.21[50]。伴随生态输水进程和地下水位的抬升,塔里木河下游胡杨林生态系统自然植被面积从2000年的492 km^2扩大到2020年的1423 km^2,增幅达到188.00%。其中,2020年塔里木河下游低、中、高覆盖度的植被较2000年分别增加20.80%,448.00%和190.00%,自然植被在多年间随输水量变化呈上下波动[14,51-52]。有研究显示,下游植物种类由输水前的9科13属17种,增加到输水后的15科36属46种[52],但样地调查发现物种多样性较高的区域仅发生在河漫滩与试验漫溢区,且多为抗干扰能力较弱的草本和半灌木,而胡杨林群落内物种多样性变化不大。输水改善了胡杨林群落内植被的长势,但超过85%的群落植被分布格局表现为聚集分布,且受输水影响明显并对输水量响应敏感,胡杨林群落多处于恢复演替的初级阶段,尚难以自我维持并恢复,在输水量下降的年份均出现不同程度逆向演替,整个群落稳定性依然不足[29,48,53]。

4 生态输水及胡杨林生态系统恢复的局限性

塔里木河下游的生态输水工程取得了较好的生态与社会效益,是新疆和我国西北干旱区内陆河流域综合治理与生态修复较为成功的案例。回顾过去20 a生态输水的历程与塔里木河下游胡杨林生态系统的恢复研究,可以发现一些不足:

(1) 生态输水影响范围有限,下游胡杨林种群退化态势尚未彻底扭转。过去20 a塔里木河下游实施的生态输水主要沿齐文阔尔河与老塔里木河河道下泄,生态水通过下渗与侧渗补给两岸地下水和包气带,地下水影响范围有限,在1000 m左右[14],对胡杨种群更新明显改善也多在近河道300 m以内[6,30],胡杨依然主要分布在距河700 m的狭窄范围内[26]。目前单一沿河道的生态输水方式缺乏胡杨林群落植被落种更新与有效恢复所需的洪泛环境[5],这在一定程度上限制了生态输水的整体效益[14]。下游胡杨种群更新乏力、年龄结构老化、群落稳定性不佳的退化态势尚未彻底扭转[44,54]。

(2) 生态水量保障水平与调度管理方案有待提高与完善。向塔里木河下游输送的生态水量在很大程度上仰赖上游各源流的来水保障。过去20 a是塔里木河流域上游各源流区及干流区耕地面积增加最为迅速的时段,尤其是塔里木河干流,灌溉面积的增加速度及幅度较各源流更大[55]。持续增长的灌溉面积和农业用水是流域“三生”用水供需矛盾加剧的主要原因,也在一定程度上增加了下游生态需水保障的不确定性。过去20 a的生态输水调度管理相对粗放,有待优化,最大与最小输水量相差可达100倍以上,2007—2009年3 a下泄生态水量不足0.25×10^8 m^3,2017年下泄水量单年曾超过12×10^8 m^3,入台特玛湖水量2.30×10^8 m^3[14],湖面水域最大超过550 km^2,对流域丰枯情景下的水资源调控与生态输水的管理有待优化。

(3) 下游胡杨林生态系统依然脆弱,稳定性有待提高。生态输水受上游源流丰枯与流域“三生”用水供需关系影响,在输水时间与输水量上仍存在较大不确定性,整体波动较大[14]。对生态输水量极为敏感的塔里木河下游胡杨林生态系统植被格局与植被群落结构尚不稳定[14,54],胡杨种群结构老化,更新整体乏力,胡杨幼株占比不足10%[44]。遇枯水年,生态输水量减少,塔里木河下游地下水位会快速下降、矿化度上升,且沿河胡杨林生态系统植被盖度下降、胡杨径向生长降低等[14,53],生态系统整体仍然较为脆弱,稳定性和自我维持能力有待提升。

5 建 议

(1) 充分利用下游新老河道与水系汊道,开展水系连通建设与包括节制闸、引水闸等生态输水辅助设施建设;构建塔里木河干流与孔雀河、纳绅河及齐文阔尔河与老塔河河道间的河-河连通体系,增大生态输水影响范围,共同恢复包括孔雀河下游与塔里木河下游组成的“绿色走廊”。

(2) 明确并分阶段科学规划塔里木河下游生态修复范围与恢复目标,科学确定台特玛湖恢复水域面积与入湖生态水量,优化输水方案;建议水头到

达台特玛湖后即由上而下分段实施有控制漫溢，将生态输水措施与塔里木河下游胡杨生繁规律相契合，在胡杨落种期实施有控制的人造洪泛环境，优先对近河道种群结构相对较好的胡杨群落实施面上给水，促进其有性繁殖与林下植被层恢复；建立塔里木河下游胡杨苗圃，围绕库-格（库尔勒-格尔木）铁路、218国道和乌-尉（乌鲁木齐-尉犁）高速公路的生态防护科学规划生态补植，结合多种措施改善下游胡杨林退化的种群结构与群落格局，促进下游胡杨林生态系统有效恢复重建。

（3）进一步完善塔里木河流域水资源管理体制，强化流域水资源的统一调配管理，优化并加强最严格水资源管理的水量管控目标，恢复并强化塔里木河干流“生态河流”的属性，保障下游生态输水常态化与输水时间、输水量的稳定，减少输水波动与不确定因素，促进下游生境稳定恢复，逐步增强塔里木河下游胡杨林生态系统的稳定性与恢复力。

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Ecosystem restoration of *Populus euphratica* forest under the ecological water conveyance in the lower reaches of Tarim River

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Abstract: The desert riparian forest distributed in the Tarim River Basin, with *Populus euphratica* Oliv. as the dominant species, is an important desert forest ecosystem in Central Asia. It provides multiple ecological services for the region, including resource supply, climate regulation, sand protection, soil and water conservation, and biodiversity protection, and an important *P. euphratica* gene pool. However, because of the large-scale development of water and soil resources in the upper reaches of the Tarim River Basin, the spatial distribution of water resources in its upper and lower reaches is gradually imbalanced, resulting in a 400-km river cutoff in the lower reaches of the Tarim River. As a result, *P. euphratica* forest ecosystems in the lower reaches of the basin were seriously degraded, desertification intensified, biodiversity was significantly reduced, and the ecological environment deteriorated day by day. In 2000, the Chinese government began to implement an ecological restoration project in the Tarim River and enforce ecological water conveyance to the lower reaches to save the dying *P. euphratica* forest. On the basis of the literature review, in this paper, the restoration of *P. euphratica* forest ecosystems under ecological water conveyance in the last 20 years in the lower reaches of the Tarim River was discussed and analyzed. Ecological water conveyance significantly raised the groundwater level, reduced the groundwater salinity and soil drought index, and effectively improved the habitat of *P. euphratica* forest ecosystems in the lower reaches of the Tarim River. The rejuvenation of *P. euphratica* was obvious: its crown width increased by 511.20% at 50 m away from the river, and its crown was full within 500 m away from the river; the average ratio of dead branches was less than 0.15. Because of water conveyance, on average, the radial growth of *P. euphratica* trunk increased by 62.80%, and the vegetation area of the desert riparian forest with *P. euphratica* as the constructive species increased from 492 km^2 in 2000 to 1423 km^2 in 2020. Low-, medium-, and high-coverage vegetation areas increased by 20.80%, 448.00%, and 190.00%, respectively, in the lower reaches of the Tarim River. The ecological environment and vegetation community in the lower reaches of the Tarim River were sensitive to and fluctuated with changes in water conveyance. The existing ecological water conveyance mode barely ensured the effective regeneration of the *P. euphratica* forest in the lower reaches because of its lack of surface hydrological processes, and the *P. euphratica* population still maintained the "inverted pyramid" degradation age class structure after 20 years of ecologic water conveyance. There were significant sex ratio bias and sexual spatial segregation in the *P. euphratica* community in the lower reaches of the Tarim River, which was still in the primary stage of restoration and succession, and the degradation trend of the downstream *P. euphratica* community had not been completely reversed. On the basis of the review, in this paper, the problems in the ecological restoration of the lower reaches of the Tarim River were discussed, and suggestions for "optimizing the water conveyance scheme, expanding the water receiving area, and taking more active restoration measures" were put forward.

Key words: Tarim River; ecological water conveyance; *Populus euphratica*; ecological restoration